

Polymers based on vinylcyclohexane

Compared with polycarbonates, which are currently used for the production of optical data storage media, polymers based on vinylcyclohexane which exhibit satisfactory
5 mechanical properties have a higher viscosity at the same temperature over a broad range of low shear rates.

The accurate moulding of pits which are smaller and disposed more closely together than those cited in EP-A 317 263 and US 4,911,966, and of the grooves which are
10 possible nowadays, is essential for high densities of data storage of > 5 Gbytes, particularly > 10 Gbytes.

The method of producing polymers based on vinylcyclohexane which is described in EP-A 317 263 and the use thereof as substrates for optical discs result in a molecular
15 weight which is too low compared with that which would ensure the operationally reliable production thereof (comparative example 1). The mechanical properties of the homopolymers described there are not very suitable for the production of optical data storage media.

20 The method described in US 4,911,966 only results in partially hydrogenated products (<97 %), and most of the examples comprise degrees of hydrogenation of <86 %. According to the prior art, partially hydrogenated systems exhibit inadequate transparency (DE-AS 11 31 885 (= GB 933 596)). The partially hydrogenated systems which are disclosed are turbid, and are unsuitable for applications as optical substrates
25 which are penetrated by a laser beam. Partially hydrogenated systems also have the disadvantage that their glass transition temperature depends on the degree of hydrogenation. In an industrial process, an adjustment of the degree of hydrogenation and thus of the thermal properties of the optical substrate can only be reproducibly implemented by expending considerable engineering effort and at considerable cost.

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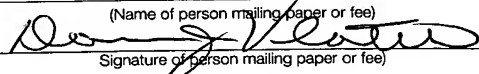
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Moreover, for the most part the partially hydrogenated products which are cited in US 4,911,966 have a molecular weight which is far too low for the operationally reliable production of substrates for optical data storage media.

- 5 The aforementioned patent specifications do not mention the quality of moulding of pit and groove structures or their existence in principle by means of the substrates cited there.

- 10 Optimised molecular weights and molecular weight distributions are essential for satisfactory mechanical properties, and at the same time good melt flow properties are essential for the moulding of pit and groove structures of high-density optical data storage media.

- 15 A molecular weight which is possibly too high can lead to problems with the moulding of pits and grooves, as a consequence of too high a viscosity.

- 20 The substrates according to the present invention, which comprise a polymer based on vinylcyclohexane with a narrow molecular weight distribution or a mixture thereof with a low molecular weight component, are distinguished by their good level of mechanical properties and by their good melt flow properties.

- 25 It is thereby possible to produce optical discs in an operationally reliable manner by injection moulding, and the discs can subsequently be handled without their bending or breaking.

Thinner substrates can be produced which have layer thicknesses less than 1.1 mm, of 0.6 mm thickness for example, and which at the same time exhibit satisfactory mechanical properties.

- 30 On account of these properties, the materials can be used very satisfactorily as substrates for optical data storage media.

Satisfactory mechanical properties are also required for other optical substrates which do not require mechanical indentations in the form of pits and grooves, for example, and have to be accompanied by a low level of birefringence, a low moment of inertia, a high level of dimensional stability when hot, a high modulus of elasticity, low water
5 absorption and low density. These requirements are also met by the substrates according to the invention.

The present invention relates to polymers of vinylcyclohexane with an absolute molecular weight M_w from 100,000 to 450,000 g/mol or a mixture thereof with a low
10 molecular weight component with an absolute molecular weight from 1000 to less than 100,000 g/mol, wherein the molecular weight distribution is characterised by a polydispersity index ($PDI = M_w/M_n$) of 1 to 3 and the maximum melt viscosity is 1000 Pa.s, as measured at 300°C and at a shear rate of 1000 sec⁻¹.

15 Any oligomeric fraction with a molecular weight M_w of up to 3000 g/mol which may possibly be present is not taken into account in the calculation of the polydispersity index.

Any oligomeric fraction with a molecular weight of up to 3000 g/mol which may be
20 present amounts to less than 5 % of the weight of the polymer.

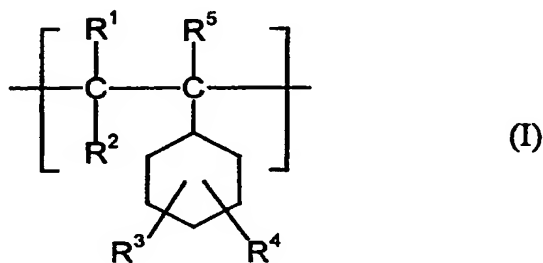
The molecular weight M_w of the high molecular weight polymer (homopolymer) preferably ranges from 200,000 to 450,000 g/mol⁻¹, and ranges in particular from 200,000 to 400,000 g/mol⁻¹.

25 The molecular weight M_w of a high molecular weight copolymer or block polymer preferably ranges from 100,000 to 400,000 g/mol⁻¹, and ranges in particular from 100,000 to 250,000 g/mol⁻¹.

30 The molecular weight M_w of the low molecular weight component generally ranges from 1000 to 100,000 g/mol⁻¹, preferably from 7000 to 90,000 g/mol⁻¹, most preferably from 10,000 to 90,000 g/mol⁻¹.

The molecular weight distribution of the respective component is characterised by a polydispersity index ($PDI = M_w/M_n$) from 1 to 3.

- 5 In the case of mixtures, the proportion of low molecular weight component with respect to the weight of the mixture of high molecular weight and low molecular weight polymers generally amounts to up to 70 % by weight, preferably 5 to 60 % by weight, most preferably 10 to 50 % by weight.
- 10 A polymer based on vinylcyclohexane is preferred both for the high molecular weight and for the low molecular weight component. This polymer comprises a recurring structural unit of formula (I)



wherein

- 15 R^1 and R^2 , independently of each other, denote hydrogen or a C_1 - C_6 alkyl, preferably a C_1 - C_4 alkyl,
- 20 R^3 and R^4 , independently of each other, represent hydrogen or a C_1 - C_6 alkyl, preferably a C_1 - C_4 alkyl, particularly methyl and/or ethyl, or R^3 and R^4 jointly represent an alkylene, preferably a C_3 or C_4 alkylene (comprising a condensed- on 5- or 6-membered cycloaliphatic ring),
- R^5 represents hydrogen or a C_1 - C_6 alkyl, preferably a C_1 - C_4 alkyl,

R^1 , R^2 and R^3 , independently of each other, represent hydrogen or methyl in particular.

5 Apart from stereoregular head-to-tail linkages, the concatenation of the above structural units can comprise a small proportion of head-to-head linkages. The vinylcyclohexane-based polymer can be branched via centres, and can have a star configuration structure for example.

10 Comonomers can be contained in an amount which generally ranges from 0 to 80 % by weight, preferably from 0 to 60 % by weight, most preferably from 0 to 40 % by weight, with respect to the finished polymer. Polymers are preferred which comprise recurring structural units of formula (I) and which are formed from one monomer or from a mixture of monomers.

15 The following substances can preferably be used as comonomers and incorporated in the polymer during the polymerisation of the starting polymer (a polystyrene which is optionally substituted): olefines which generally comprise 2 to 10 C atoms, such as ethylene, propylene, isoprene, isobutylene or butadiene for example, C_1 - C_8 , preferably C_1 - C_4 alkyl esters of acrylic or methacrylic acid, unsaturated cycloaliphatic
20 hydrocarbons, e.g. cyclopentadiene, cyclohexene, cyclohexadiene, norbornene which is optionally substituted, dicyclopentadiene, dihydrocyclopentadiene, tetracyclodecene which is optionally substituted, styrenes with alkylated nuclei, α -methylstyrene, divinylbenzene, vinyl esters, vinylic acids, vinyl ethers, vinyl acetate, vinyl cyanides such as acrylonitrile or methacrylonitrile, maleic anhydride, and mixtures of these
25 monomers.

The polymers can have a linear chain structure, or can also comprise branching sites due to co-units (e.g. graft copolymers). The branching centres may comprise star configuration polymers or branched polymers. The polymers according to the
30 invention can comprise other forms of what is a primary, secondary, tertiary or optionally a quaternary polymer structure, such as a helix, a double helix, a folded sheet, etc., or mixtures of these structures.

Homopolymers formed from a monomer corresponding to formula (I) are particularly preferred.

- 5 Polymers which are particularly preferred for the high molecular weight component include homopolymers of a monomer corresponding to formula (I), most preferably hydrogenated styrene-isoprene polymers, particularly block copolymers, and can be used either on their own or as a mixture.
- 10 Polymers which are particularly preferred for the low molecular weight component include homopolymers of a monomer corresponding to formula (I), (block) copolymers, most preferably hydrogenated styrene-isoprene polymers, particularly hydrogenated styrene-isoprene polymers which comprise 3 to 8, preferably 3 to 5, radial members. The low molecular weight component can be present either as one
- 15 polymer or as mixtures of said polymers.

The vinylcyclohexane-based polymers can have an atactic, a predominantly syndiotactic or a predominantly isotactic diad configuration.

- 20 Amorphous substrates are also preferred which comprise a predominantly syndiotactic configuration of the vinylcyclohexane units and which are characterised in that the amount of diads is greater than 50.1 % and less than 74 %, most preferably greater than 52 % and less than 70 %.
- 25 Methods of elucidating the microstructure by means of ^{13}C - ^1H correlation spectroscopy of the methylene carbon atoms of a polymer backbone are generally known and are described by A.M.P. Ros and O. Sudmeijer (A.M.P. Ros, O. Sudmeijer, Int. J. Polym. Anal. Charakt. (1997), 4, 39) for example.
- 30 The signals of crystalline isotactic and syndiotactic polyvinylcyclohexane are determined by means of two-dimensional NMR spectrometry. In the 2 D CH correlation spectrum, the methylene carbon atom (in the polymer backbone) of

isotactic polyvinylcyclohexane splits into two separate proton signals, and indicates a purely isotactic diad configuration. Syndiotactic polyvinylcyclohexane, on the other hand, only exhibits one signal for the C 1 carbon atom in the 2 D CH correlation spectrum. The amorphous syndiotactic-rich polyvinylcyclohexane according to the
5 invention exhibits an integral excess of intensity of syndiotactic diads compared with the isotactic diad configuration.

VCH polymers are produced by polymerising derivatives of styrene with corresponding monomers, by a radical, anionic or cationic mechanism, or by means of
10 metal complex initiators or catalysts, and by subsequently completely or partially hydrogenating the unsaturated aromatic bonds (see, for example, WO 94/21694, EP-A 322 731).

Polymers based on vinylcyclohexane are produced in particular by the hydrogenation
15 of styrene derivatives which have been polymerised by an anionic or radical mechanism. The polymers according to the invention can comprise bimodal or optionally multimodal distributions over the range of polydispersity considered.

One skilled in the art in the field of anionic and radical polymerisation is aware that
20 the polydispersities of prepolymers can be adjusted between 1 and 3 (Braun, D., Praktikum der makromolekularen organischen Chemie, revised, expanded edition, Heidelberg, Huethig 1979).

The absolute (weight average) molecular weights M_w of the hydrogenated products
25 are determined by light scattering. The absolute (number average) molecular weights M_n are determined by membrane osmosis (vapour pressure osmosis). Another method of characterising the molecular weight distribution by polydispersity is the measurement of the relative molecular weights M_w and M_n by gel permeation chromatography.

30

The process generally results in practically complete hydrogenation of the aromatic units. As a rule, the degree of hydrogenation is $\geq 80 \%$, preferably $\geq 90 \%$, most

preferably > 99 % to 100 %. The degree of hydrogenation can be determined by NMR or UV spectrometry, for example.

5 The melt viscosity is determined by the oscillation method, by means of a melt viscometer of plate and cone construction. The viscosity depends on the shear rate (angular frequency), and the viscosity at 300°C and 1000 sec⁻¹ of the polymers or mixtures according to the invention is generally up to 1000 Pa.s, and preferably ranges from 5 to 500 Pa.s, most preferably from 10 to 200 Pa.s.

10 The starting polymers are generally known (e.g. WO 94/21 694).

Polymerisation can be conducted continuously, semi-continuously or batch-wise.

15 The amount of catalyst used for hydrogenation depends on the process employed; the latter can be carried out continuously, semi-continuously or batch-wise.

In a batch process, the ratio of catalyst to polymer is generally 0.3 - 0.001, preferably 0.2 - 0.005, most preferably 0.15-0.01.

20 The polymer concentrations with respect to the total weight of solvent and polymer generally range from 80 to 1, preferably 50 to 10, particularly 40 to 15 % by weight.

The starting polymer is hydrogenated by methods which are generally known (e.g. WO 94/21 694, WO 96/34 895, EP-A-322 731). A multiplicity of known
25 hydrogenation catalysts can be used as catalysts. Examples of preferred metal catalysts are cited in WO 94/21 694 or WO 96/34 896. Any catalyst which is known for hydrogenation reactions can be used. Suitable catalysts include those with a large surface area (e.g. 100 - 600 m²/g) and a small average pore diameter (e.g. 20 - 500 Å). Other suitable catalysts include those with a small surface area (e.g. ≥ 10 m²/g) and
30 large average pore diameters which are characterised in that 98 % of the pore volume comprises pores with pore diameters larger than 600 Å (e.g. about 1000 - 4000 Å) (see, for example, US-A 5,654,253, US-A 5,612,422, JP-A 03076706). Raney nickel,

nickel on silica or on silica/alumina, nickel on carbon as a support, and/or noble metal catalysts e.g. Pt, Ru, Rh, Pd, are used in particular.

- 5 The reaction is generally conducted at temperatures between 0 and 500°C, preferably between 20 and 250°C, particularly between 60 and 200°C.

The solvents which are customarily used for hydrogenation reactions are described in DE-AS 1 131 885 for example (see above).

- 10 The reaction is generally conducted at pressures from 1 bar to 1000 bar, preferably from 20 to 300 bar, particularly from 40 to 200 bar.

- 15 The vinylcyclohexane-based polymers or copolymers according to the invention are of excellent suitability for the production of optical data storage media, preferably those with densities of data storage >5 Gbyte, particularly >10 Gbyte, with respect to a disc of 120 mm diameter.

Additives, such as stabilisers and demoulding agents for example, can be added to the vinylcyclohexane-based polymers or (block) copolymers.

Examples of optical data storage media include:

- magneto-optical disc (MO disc)
- mini-disc (MD)
- 5 - ASMO (MO-7) (“advanced storage magneto-optic”)
- DVR (12 Gbyte disc)
- MAMMOS (“magnetic amplifying magneto-optical system”)
- SIL and MSR (“solid immersion lens” and “magnetic super-resolution”)
- CD-ROM (read only memory)
- 10 - CD, CD-R (recordable), CD-RW (rewritable), CD-I (interactive), photo-CD
- super audio CD
- DVD, DVD-R (recordable), DVD-RAM (random access memory);
- DVD=digital versatile disc
- DVD-RW (rewritable)
- 15 - PC + RW (phase change and rewritable)
- MMVF (multimedia video file system).

Moreover, due to their outstanding optical properties the polymers according to the invention are particularly suitable for the production of optical materials. e.g. for

20 lenses, prisms, mirrors, colour filters, etc., and are also suitable as media for holographic images (e.g. for cheque cards, credit cards, passes, and for three-dimensional holographic images). The materials can be used as transparent media on which three-dimensional structures can be inscribed, e.g. three-dimensional structures from focused coherent radiation (LASER), and can be used in particular as three-

25 dimensional data storage media or for the three-dimensional imaging of objects.

Examples

Production:

5 Examples 1 - 4: hydrogenated polystyrene (h-PS)

A 40 litre autoclave was flushed with inert gas (nitrogen). The polymer solution and catalyst were added (Table 1). After closing the autoclave, it was repeatedly pressurised with an inert gas and was then pressurised with hydrogen. After releasing
10 the pressure, the respective hydrogen pressure was set and the batch was heated with stirring to the corresponding reaction temperature. After the absorption of hydrogen had commenced, the reaction pressure was held constant. The reaction time was defined as the period from heating up the batch until the time at which the hydrogen atoms approached their saturation value.

15

After completion of the reaction, the polymer solution was filtered. The stabiliser was added, and the product was freed from solvent at 240°C and was processed further as a granular material (Examples 1 to 4, Table 1).

20 The molecular weights listed in Table 2 can be achieved by the reaction conditions employed, particularly the temperature (Table 1), and by the subsequent work-up conditions (temperature of evaporation of solvent, type of stabiliser and the concentration thereof).

25 Example 5: Production of poly(styrene-block-co-isoprene)

These syntheses were carried out using standard inert gas techniques. 138 kg abs. cyclohexane were placed in a 250 litre reactor. 6.3 kg abs. styrene were introduced into the reactor at room temperature. The temperature was raised to 55°C and
30 (0.255 mol) n-butyllithium (a 23 % solution in n-hexane) were introduced into the reactor. The reaction mixture was heated to 70°C and was stirred for 30 minutes.

1.4 kg abs. isoprene and 6.3 kg abs. styrene were simultaneously introduced into the reactor. The mixture was held at 70°C for 2 hours. The reaction solution was cooled to room temperature and a solution of 10 g 2-propanol in 500 g cyclohexane was added. The polymer solution was concentrated to 16.6 % by weight at 40 to 45°C under vacuum.

Example 6: Production of hydrogenated poly(styrene-block-co-isoprene)

22 kg of the polymer solution (Example 5) were transferred under nitrogen to a 40 litre autoclave. After adding 421.5 g Ni 5 136 P (Engelhard), the autoclave was repeatedly pressurised with nitrogen and hydrogen. The reaction solution was heated at 100 bar to 170°C. After the heat-up phase, the reaction was conducted at 150 bar, as controlled by an automated pressure device, until constant pressure was achieved, and the batch was stirred for a further two hours.

The catalyst was filtered from the polymer solution. The polymer solution was stabilised with 4000 ppm Irganox XP 420 FF, was freed from solvent at 240°C and was processed further as a granular material.

Example 7: Production of star configuration poly(styrene-block-co-isoprene)

1200 g cyclohexane, 800 g methyl-tert.-butyl ether and styrene (350 g, 3.37 mol) were transferred into a 5 litre steel autoclave. Butyllithium (1.24 g, 19.3 mmol) was added to the solution with stirring at room temperature (25°C). Polymerisation was conducted for 1.5 hours at this temperature. Thereafter, isoprene (53 g, 0.77 mmol) was added to the polymer solution. After 1.5 hours, tetramethoxysilane (0.61 g, 4 mmol) was added as a 7.5 % by weight solution in cyclohexane to the block copolymer solution. Concatenation to form the star configuration polymer was effected at 80°C for 3 hours. Thereafter, 5 ml isopropanol were added.

Example 8: Production of hydrogenated star configuration poly(styrene-block-co-isoprene)

Nickel on silica/alumina (Aldrich) was added to the polymer solution (Example 7),
5 which was then transferred to a 5 litre autoclave. The latter was repeatedly rendered
inert with nitrogen. After depressurisation, the hydrogen pressure was set at 100 bar
and the batch was heated to 180°C and held at this temperature for 6 hours. Each time
the pressure fell to 80 bar, it was increased to 100 bar again. After completion of the
reaction, the batch was cooled to room temperature, the catalyst was separated from the
10 polymer solution by filtration, and the polymer was dried under vacuum.

**Example 9: Production of a blend of hydrogenated polystyrene and
hydrogenated, star configuration poly(styrene-block-co-isoprene).**

15 The polymer (Example 8) was dissolved, as a 20 % solution, in cyclohexane/methyl-
tert.-butyl ether in a ratio of 2/1, was treated with the stabiliser Irganox XP 420 FF and
was mixed with a solution of the hydrogenated polystyrene (Example 4) in a ratio of
polymers of 50/50. The solvent was removed under vacuum and the dried polymer
was processed in an extruder to form granules.

20

The granules were processed to form moulded blanks by a CD injection moulding
process (Table 4).

Table 1

Hydrogenation of polystyrene

Example No.	Weight of polymer ²⁾ (kg)	Solvent (litres)	Weight of catalyst (g)	Reaction temp. (°C)	Hydrogen pressure (bar)	Reaction time (hours)	Degree of hydrogen-ation ¹⁾ (%)	Stabiliser (ppm)
1	5.0	15 l cyclo-hexane 10 l methyl-t-butyl ether	625 ³⁾	180	100	9.7	100	2500 Irganox* B 561
2	5.0	15 l cyclo-hexane 10 l methyl-t-butyl ether	625 ³⁾	160	100	16.5	100	2500 Irganox* B 561
3	4.8	15 l cyclo-hexane 9.1 l methyl-t-butyl ether	625 ⁴⁾	160	100	17.5	100	4000 Irganox* XP420 FF
4	4.8	15 l cyclo-hexane 1.1 l methyl-t-butyl ether	625 ⁴⁾	160	100	19	100	Irganox* XP 420 FF

5

- 1) determined by ¹H NMR spectrometry
- 2) polystyrene Type 158 k, transparent, Mw 280,000 g/mol, BASF AG, Ludwigshafen, Germany
- 3) Ni /SiO₂/Al₂O₃, 64-67 % nickel, Aldrich
- 4) Ni /SiO₂/Al₂O₃, Ni-5136 P, Engelhard, De Meern, Holland

10

* The stabilisers were commercial products of Ciba, Basle, Switzerland.

Table 2

Molecular weights Mn, Mw; PDI; and pit or groove moulding whilst simultaneously complying with the mechanical requirements for CD injection moulding

Example No.	Average molecular weight $\overline{Mn}^{1)}$ (10^3 g/mol)	Average molecular weight $\overline{Mw}^{2)}$ (10^3 g/mol)	Polydispersity PDI	Maximum processing temperature at die outlet (°C)	Mould temperature (°C)	Cracks in optical substrate (+/-)	Pit depth ³⁾ (mm)
1 A comparative	91.2	191.5	2.1	330	85	+	92
2 B according to the invention	109.8	238.4	2.2	315	70	-	110
3 A according to the invention	107.3	267.2	2.5	335	85	-	82
4 C according to the invention	108.0	259.0	2.4	350	85	-	75
6 C according to the invention	96.8	121.3	1.25	315	75	-	80
4 A according to the invention	108.0	259.0	2.4	320	100	-	122
9 A ³⁾ Mixture according to the invention	54.5 ⁴⁾ / 108.0	62.0 ⁴⁾ / 259.0	1.1 / 2.4	320	100	-	140

A = Standard digital versatile disc die, substrate produced by means of Nestal Disjet 600

B = Standard compact disc die, substrate produced by means of Nestal Disjet 600

C = High density digital versatile die with 93 mm pit depth as measured

PDI = Polydispersity

1) Absolute molecular weights M_n from the measured correlation of the GPC values of the vinylcyclohexane-based polymers with molecular weights determined by membrane osmosis

2) Absolute molecular weights M_w from the measured correlation of the GPC values of the vinylcyclohexane-based polymers with molecular weights determined by light scattering

3) determined by scanning force microscopy (AFM)

4) molecular weights M_n and M_w of the prepolymer as measured by GPC

5) 50/50 blend

Various pit depths can be obtained in an injection moulding or injection embossing process depending on the depths of the pits and grooves of the die used. The pit depth or groove depth can be varied by adjustments to the apparatus, by the mould
5 temperature and by the melting temperature of the polymer.

Example 1 A (Table 2) illustrates good pit moulding of the vinylcyclohexane-based polymer. However, the substrates of optical data storage media which were produced by injection moulding comprised fissures (termed cracks or microcracks). The
10 materials which are characterised in Examples 2 B and 3 C could be produced without the occurrence of cracks or microcracks. The vinylcyclohexane-based polymers according to the invention constitute ideal optical substrates, which at the same time facilitate good pit or groove moulding at low die temperatures without the occurrence of cracks.

15

Both Example 4 C (homopolymer) and Example 6 C (copolymer) illustrate good pit replication (75 nm/80 nm) at low mould temperatures, without the formation of cracks. Moreover, Example 6 C (copolymer) illustrates excellent pit replication at low processing and die temperatures.

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Example 9 A (a blend of a high molecular weight polymer and a low molecular weight component) also illustrates excellent pit replication without crack formation.

The CD substrates according to the invention can be produced without cracks with
25 enhanced operational reliability compared with Example 1 A..